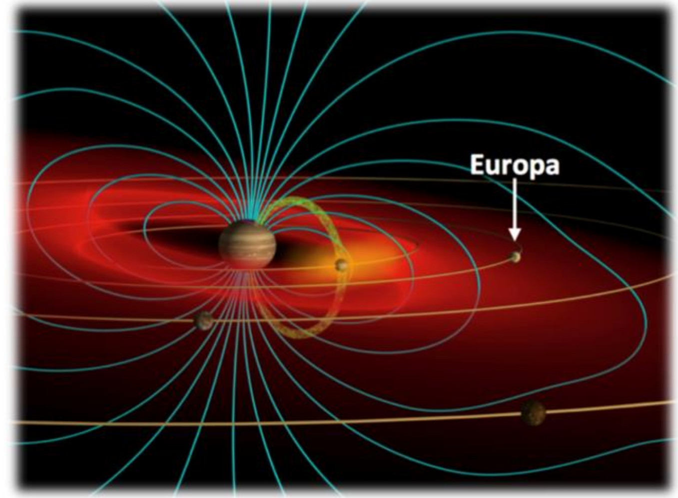
Analyses and Methods of Solid Rocket Motor Material Irradiation at Marshall Space Flight Center

Jarvis Caffrey[1], Jason Vaughn[1], Todd Schneider[1], Emily Willis[1], Adrian Soler-Luna[1], Kathryn Wiedow[2], Gennady Miloshevsky[3], Brandon Phillips[1], Erin Hayward[1], Joey Norwood[1]

[1]NASA Marshall Space Flight Center, Huntsville AL (e-mail: jarvis.a.caffrey@nasa.gov)
[2]JACOBS ESSCA Contract - NASA MSFC, Huntsville AL
[3]Virginia Commonwealth University, Richmond VA

Europa Lander De-Orbit Stage Radiation Approach



- Jupiter's magnetic field produces the most intense planetary radiation environment in the solar system

- Radiation burden to any Europa mission is:
  - Complex (many types of radiation)
  - Non-uniform (dose varies by O.O.M.)
  - Uncertain (limited body of knowledge)

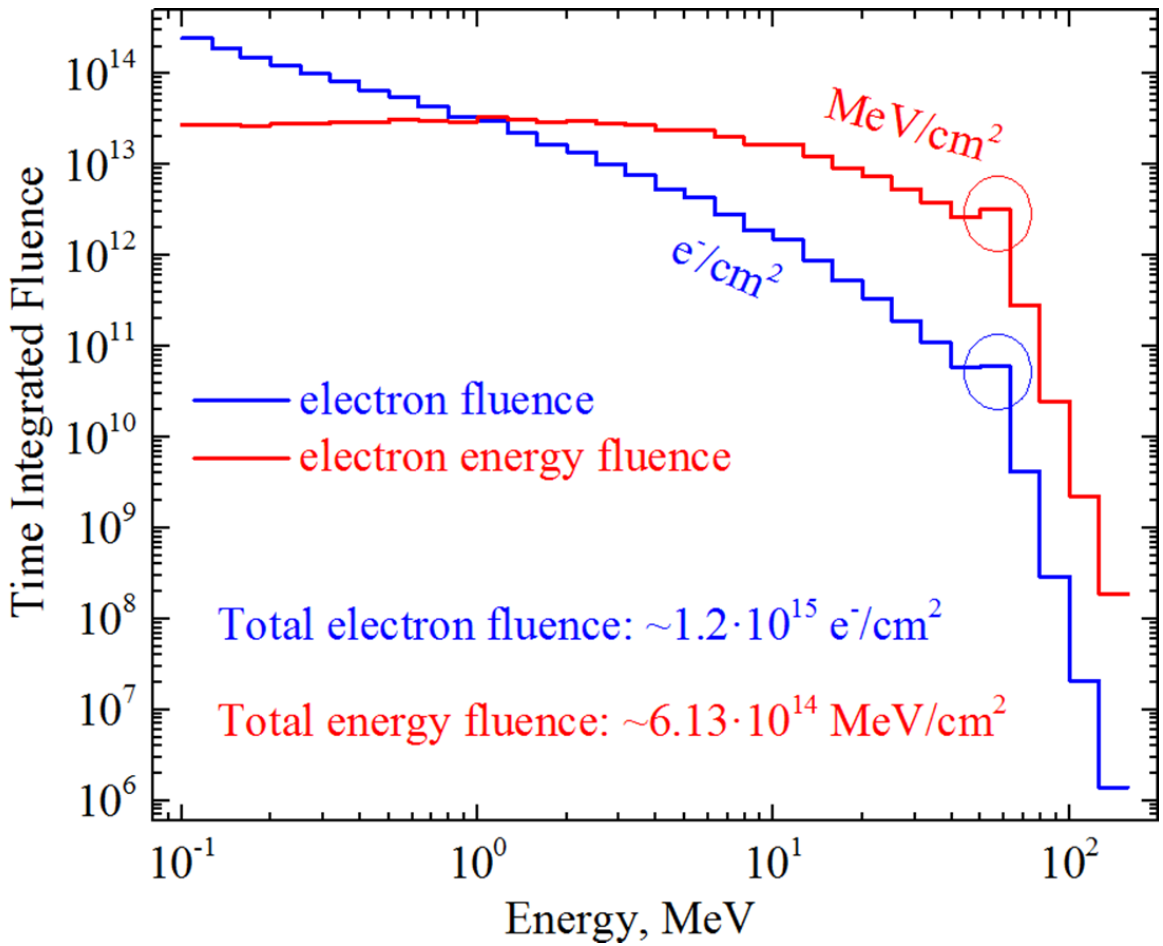
- Significant level of effort is required to understand and mitigate this risk

- Europa De-Orbit Stage Concept embraces standard JPL policy, design methods, and processes for radiation tolerance
  - Radiation Design Factor (RDF) of 2x expected total ionizing dose (TID) is incorporated in DOS design and testing philosophy

DOS materials will be tested and designed to operate in an environment ≥ 2x expected Total Ionizing Dose (TID)

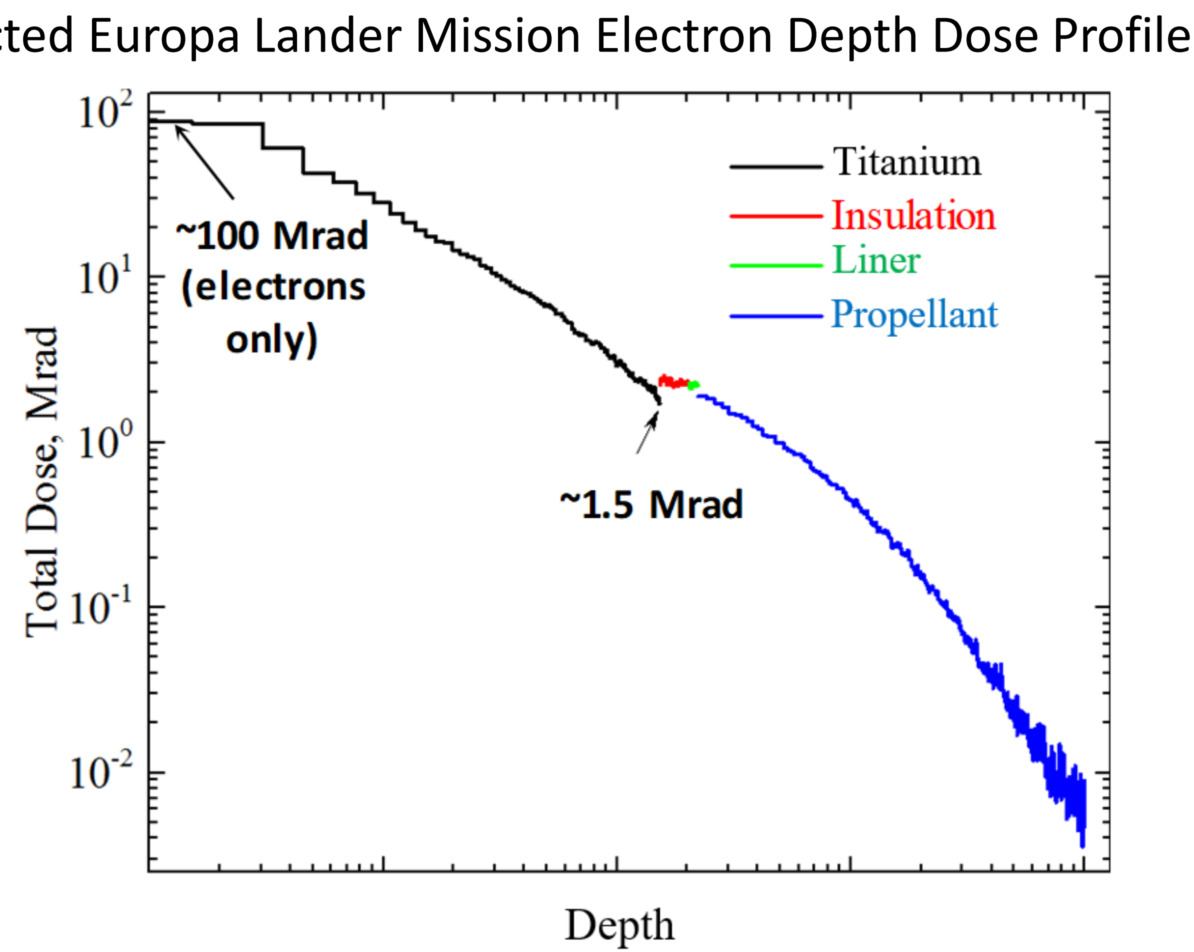
Jovian Radiation Environment Description

Projected Europa Lander Mission Electron Fluences



Graph from Miloshevsky, G. Caffrey, J.A., Jones, J.E., Zoladz, T.F., "Materials Degradation in the Jovian Radiation Environment" NASA/TM-2017-219848 – MSFC Faculty Fellowship Program, 2017
Compiled JPL fluence data by Norwood (NASA/MSFC)

Expected Jovian Radiation Dose in SRM

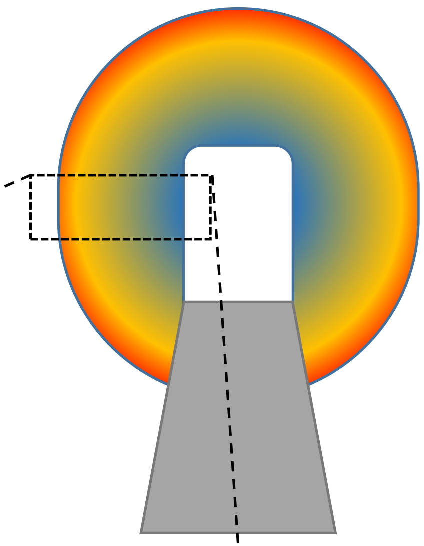


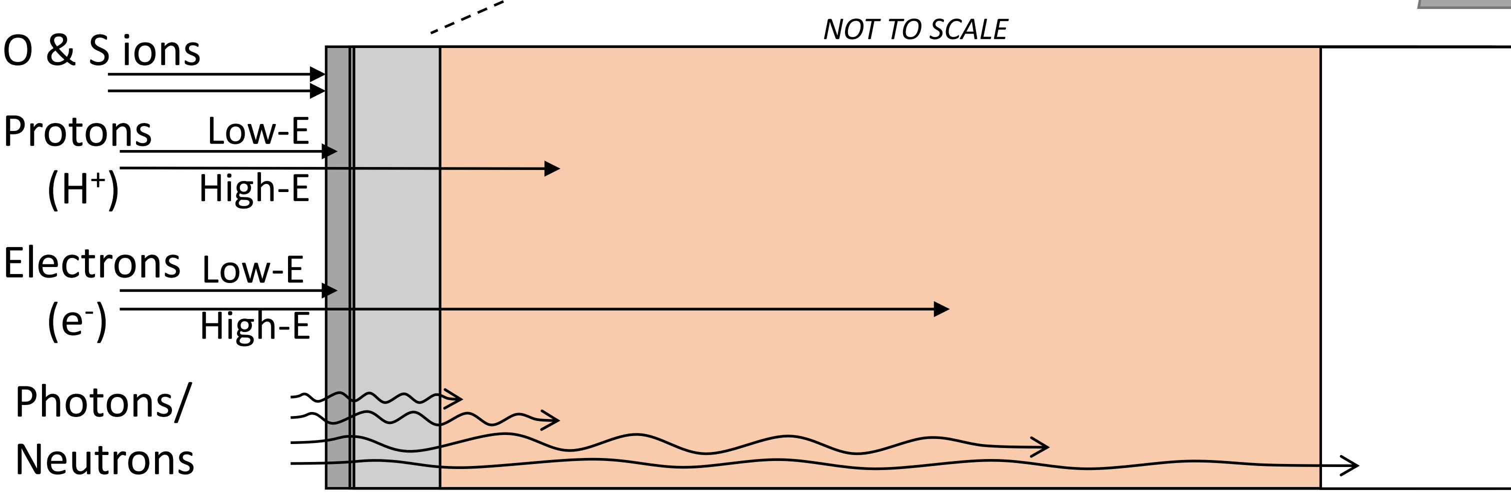
Histogram from Miloshevsky, G. Caffrey, J.A., Jones, J.E., Zoladz, T.F., "Materials Degradation in the Jovian Radiation Environment" NASA/TM-2017-219848 – MSFC Faculty Fellowship Program, 2017 using MONSOL. Compiled JPL mission fluence data by Norwood (NASA/MSFC)

Dose accumulated in the Jovian radiation environment is **very dependent upon position** on and within the DOS

Radiation Environment in Spacecraft

- **Type and intensity of exposure varies strongly with position**
- Larger Ions (Oxygen & Sulfur) stop quickly (μm)
- Electrons and higher energy protons penetrate more ($mm - cm$)
- Secondary neutral radiation penetrates deeply ($>cm$)





High energy electrons are primary dose driver inside the case

Requirements / Design Principles

From JPL-43913 – Design, Verification/Validation & Ops Principles for Flight Systems (Design Principles), Rev. 6 – Oct 4, 2012

- **4.12.1.5 Radiation Design Factors**

Definition: Radiation Design Factor (RDF) = electronic part capability/electronic part expected local environment.

  - 4.12.1.5.1 **Nominal RDF**- The design shall meet a RDF of at least 2 through to the end of the primary mission.

    (Associated Lesson(s) Learned: NEN #0384)

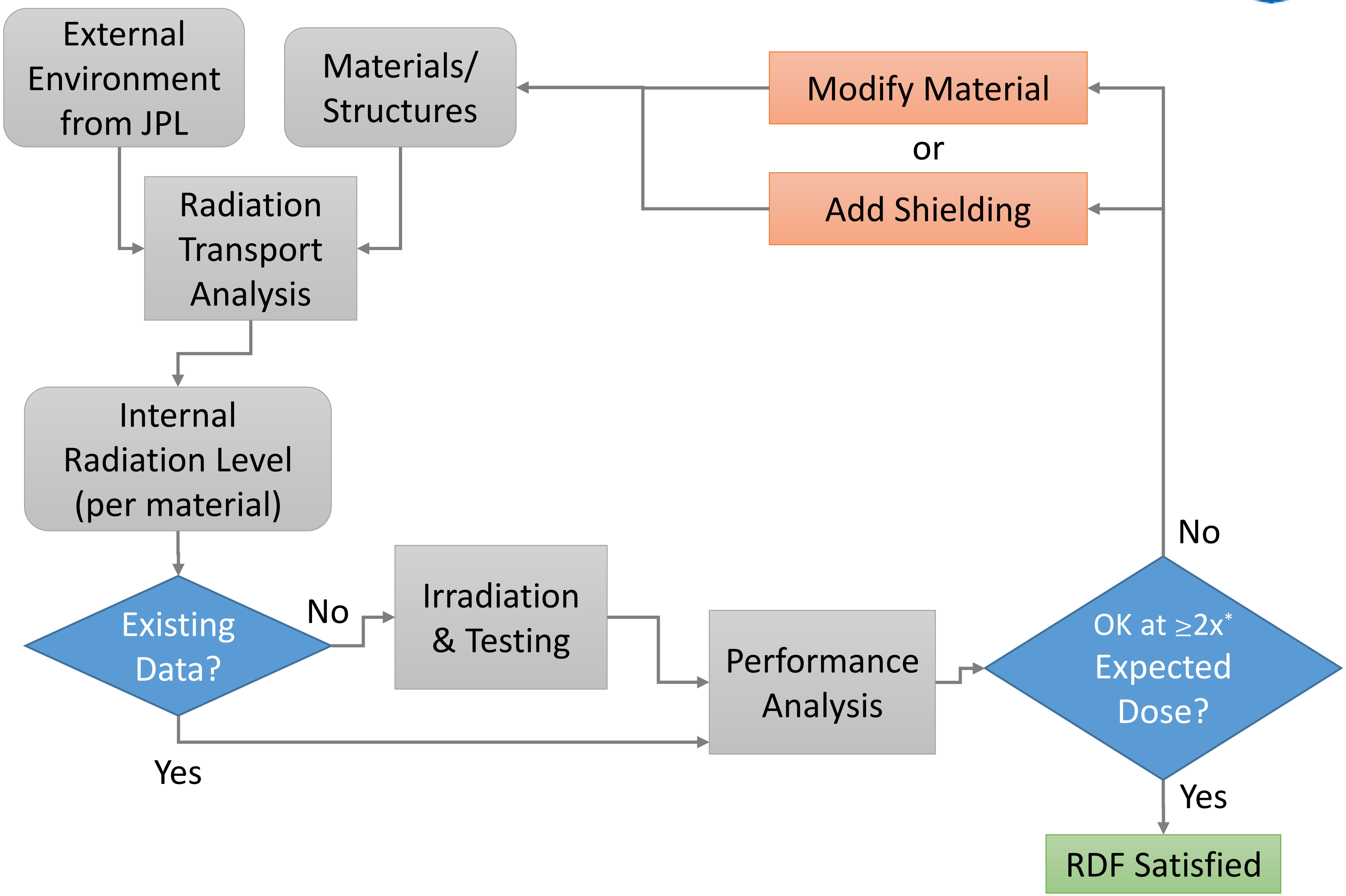
    Rationale: Provides margin to account for uncertainties, e.g. related to the space environment.

  - 4.12.1.5.2 **Spot shielding**- The design shall meet a RDF of at least 3 through to the end of the primary mission in those locations where "spot shielding" is used.

    Rationale: The greater RDF for those parts where spot shielding is to be used is to account for uncertainties in part capabilities and transport modeling.

  - 4.12.1.5.3 **Science instruments**- Science instruments shall satisfy the RDF of 4.12.1.5.1 and/or, as appropriate, 4.12.1.5.2.

Radiation Assessment – General Workflow



*3x Expected level if spot-shielding is applied

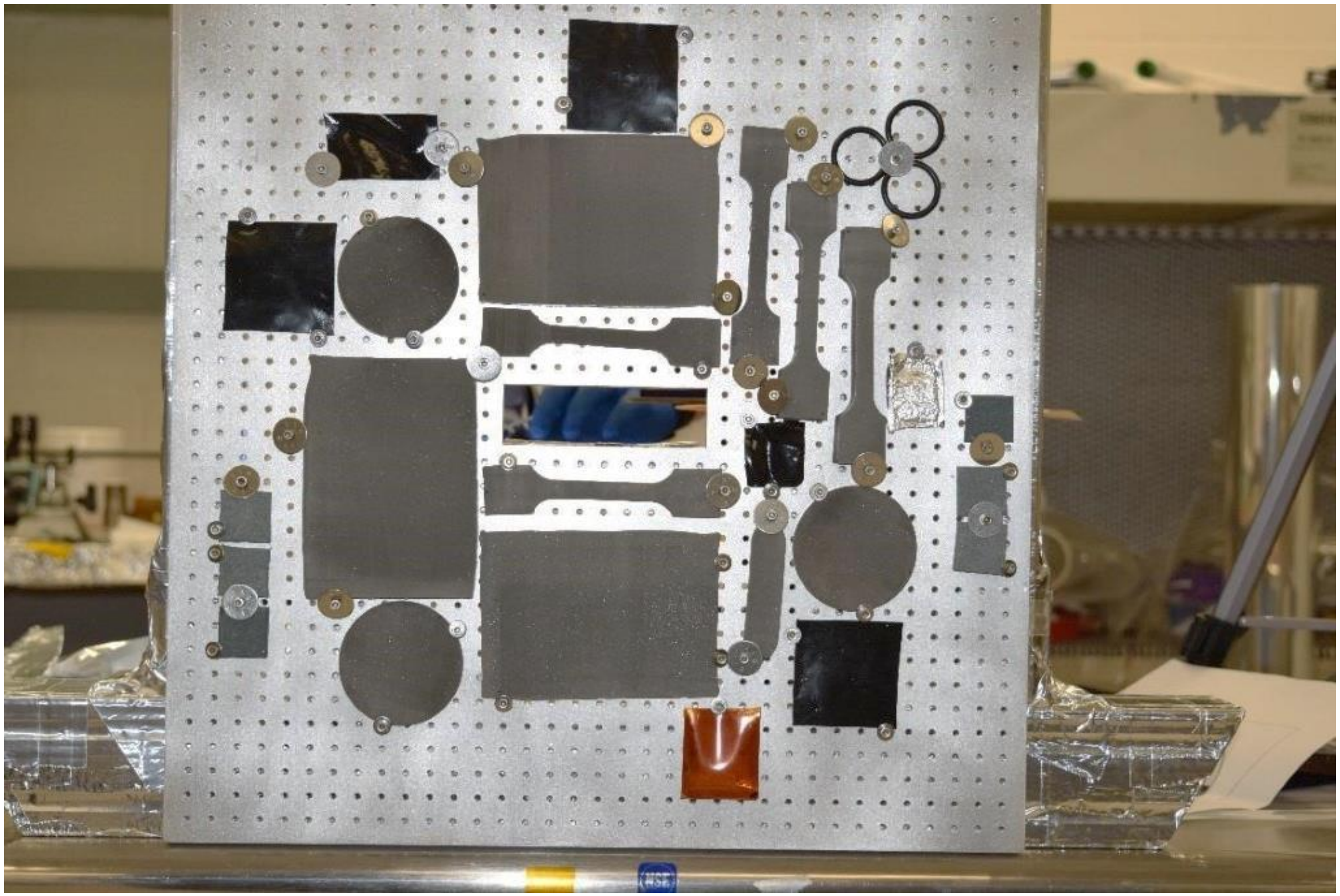
Subscale/Piecewise Irradiation

- Individual subscale components are irradiated using an electron beam at MSFC
  - Combined Environment Effects Facility (CEEF)
  - POC Jason Vaughn
- Delivers electron dose directly, up to 2.5 MeV energy
  - Recall some Europa e^- are >100 MeV
- Range in materials is limited by max energy
  - Range depends on density
  - Propellant samples less than 0.4” can be irradiated uniformly if flipped

CEEF Pelletron facility at MSFC

Preparing sample plate with live propellant

Electron Beam Sample Plate



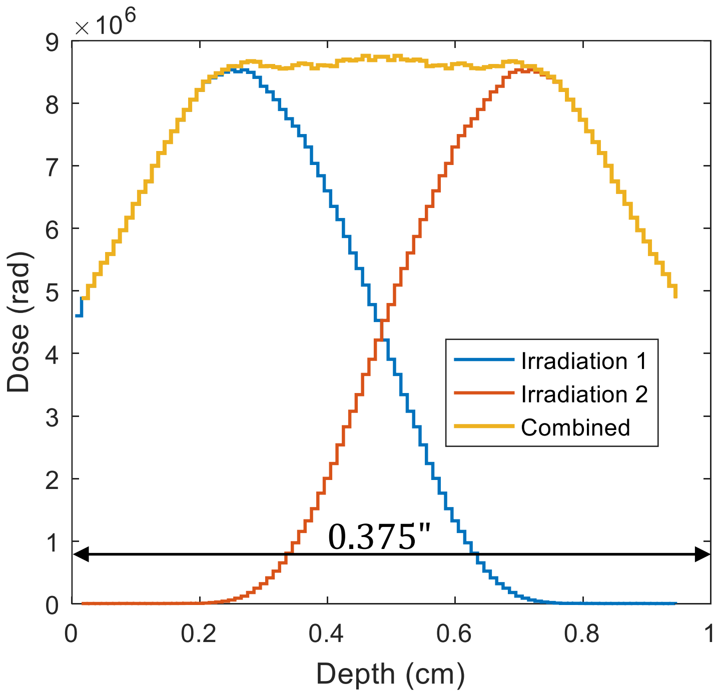
Soler-Luna, A., Wiedow, K., Caffrey, J., Vaughn, J. Determination of the effects of Jovian radiation on mechanical and ballistic properties of solid rocket propellant for the Europa deorbit stage braking motor. JANNAF Conference paper in press, May 2019.

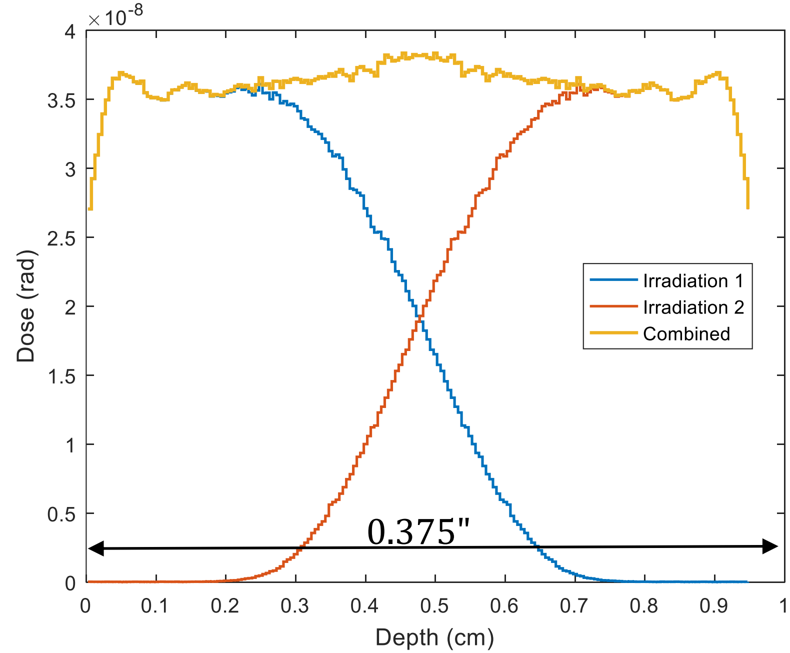
Electron Irradiation Uniformity Challenges

- Multiple effects create non-uniformities:
  - Penetration depth of electrons
    - This non-uniformity happens in the direction of the beam
    - The bulk of the radiation gets stopped in the first ¼” of propellant for highest energy electrons
  - Mono-energetic depth-dose curve
    - Dose changes with depth: starts low, goes up, then drops to zero
    - Peak dose occurs deeper inside sample, away from beam-facing surface
  - Edge effects of surfaces parallel to the direction of the beam
    - Energy deposition is a diffusive process due to internal scattering
    - Energy deposition is lower (by about half) at those edges

Depth Effects

Problem:	Limited Depth	Reduced Surface Dose
Solution:	Irradiate both sides	Multiple energy levels



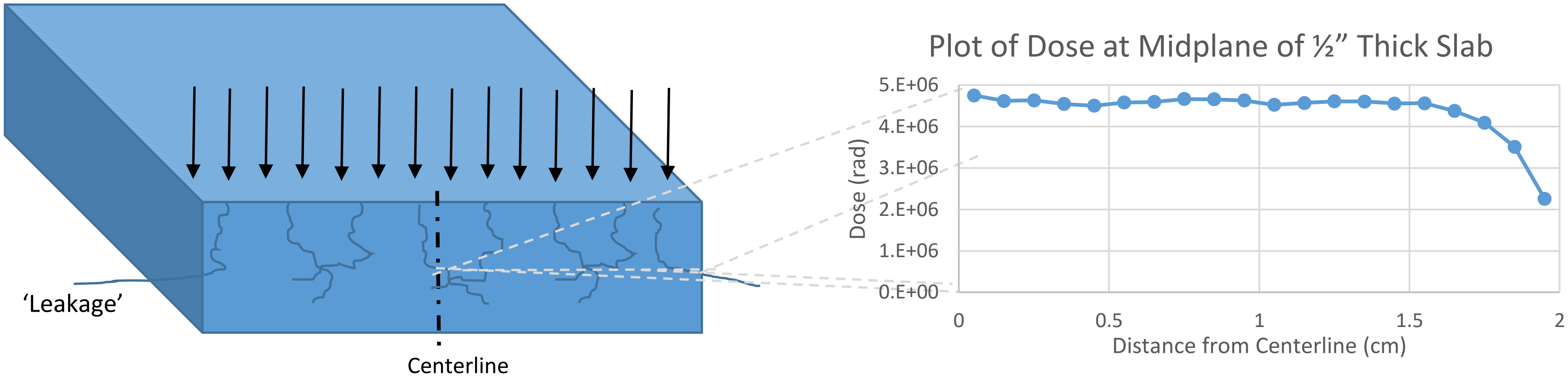


2.4 MeV
1.8×10^{14} electrons/cm^2
0.375” of Live Propellant
$\rho \cong 1.8$ g/cm^3

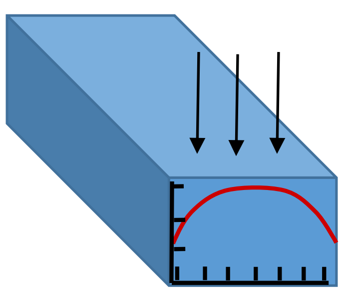
Same as to the left,
but split fluence as:
0.5 MeV: 10%
0.9 MeV: 15%
2.4 MeV: 75%

Edge Effects

Edges parallel to beam experience ‘leakage’ of electrons

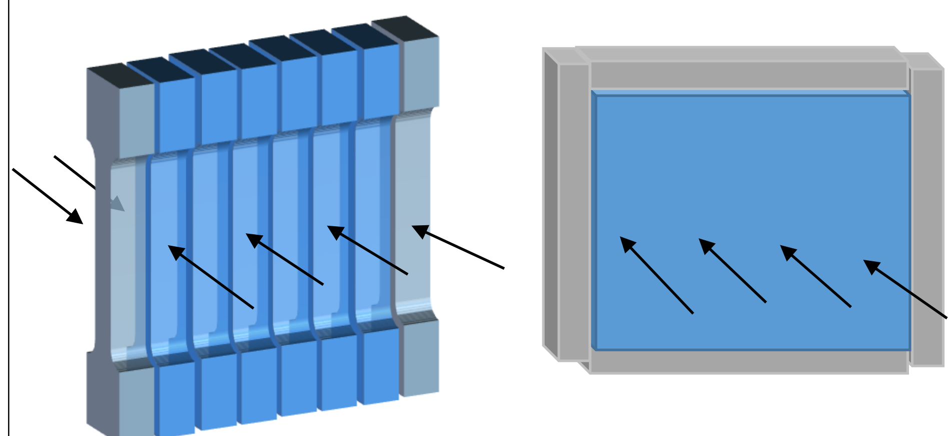


Cutaway of sample irradiated with vacuum boundaries on sides

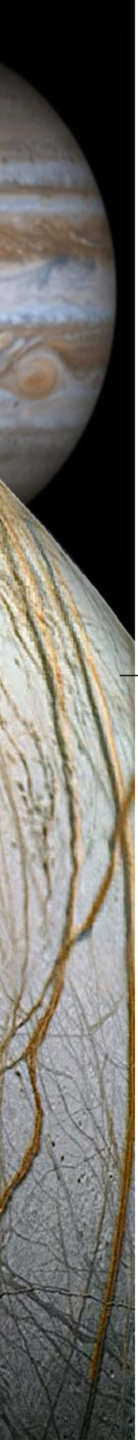


Relative Dose Profile Across Width of Sample

Solution: Stack/surround/discard

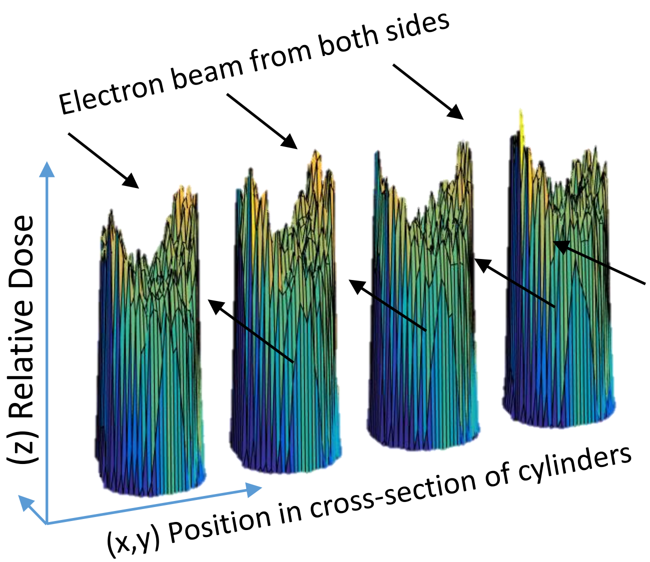


Outer-most material receives worst uniformity.
Sacrificial sample material is recommended.
Dissimilar material is okay.



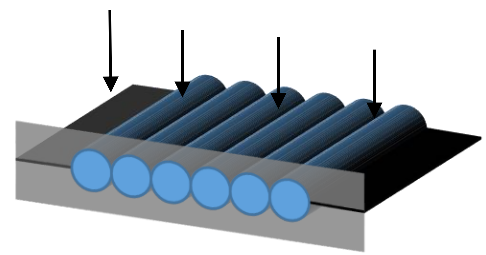
Non-slab specimens

Complex Non-uniformities



Leakage effects complicated and overwhelmed by irregular dose depth distribution due to non-uniform thickness across the breadth of the beam.

Solution:
Encase samples in material

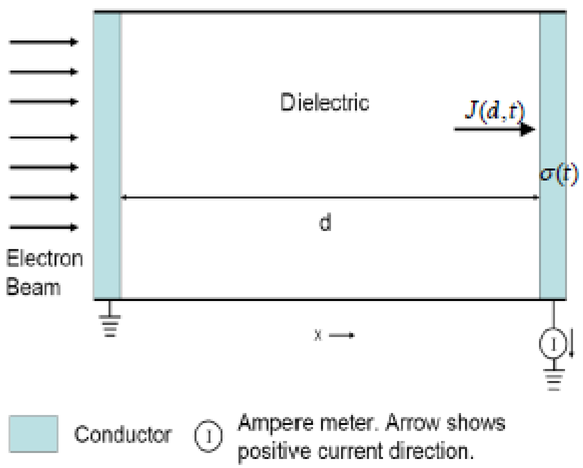


- Resembles a slab-like geometry
- Similar material preferred, but not required
- Also serves to secure more delicate samples

Internal Electrostatic Discharge Analysis (iESD)

Simulation of Arcing Risk

- Method:
  - Use NUMIT2.0 to simulate the buildup of the electric field in the material
    - 1-D simulation of a slab of material between two grounded, thin metal plates
    - Compare the simulated electric field with the dielectric strength of the material.
    - If the electric field is near the dielectric strength, arcing may occur.

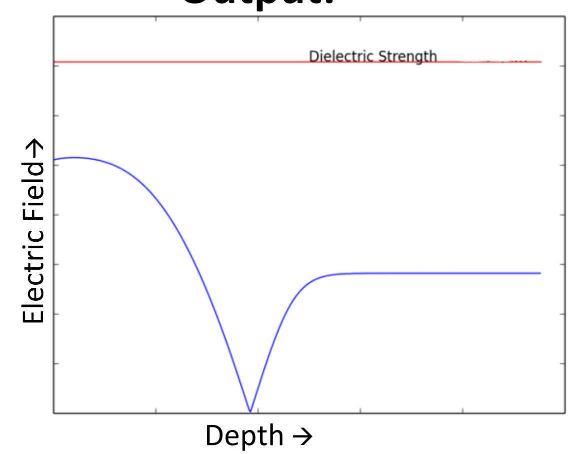


Reference:
Kim, W. et al, NUMIT 2.0: the latest version of the JPL internal charging analysis code, Spacecraft Charging Technology Conference.

Model Inputs:
Beam specifications (determined by MSFC)
Material atomic composition & density
Volume Conductivity
Dielectric Strength
Dielectric Constant

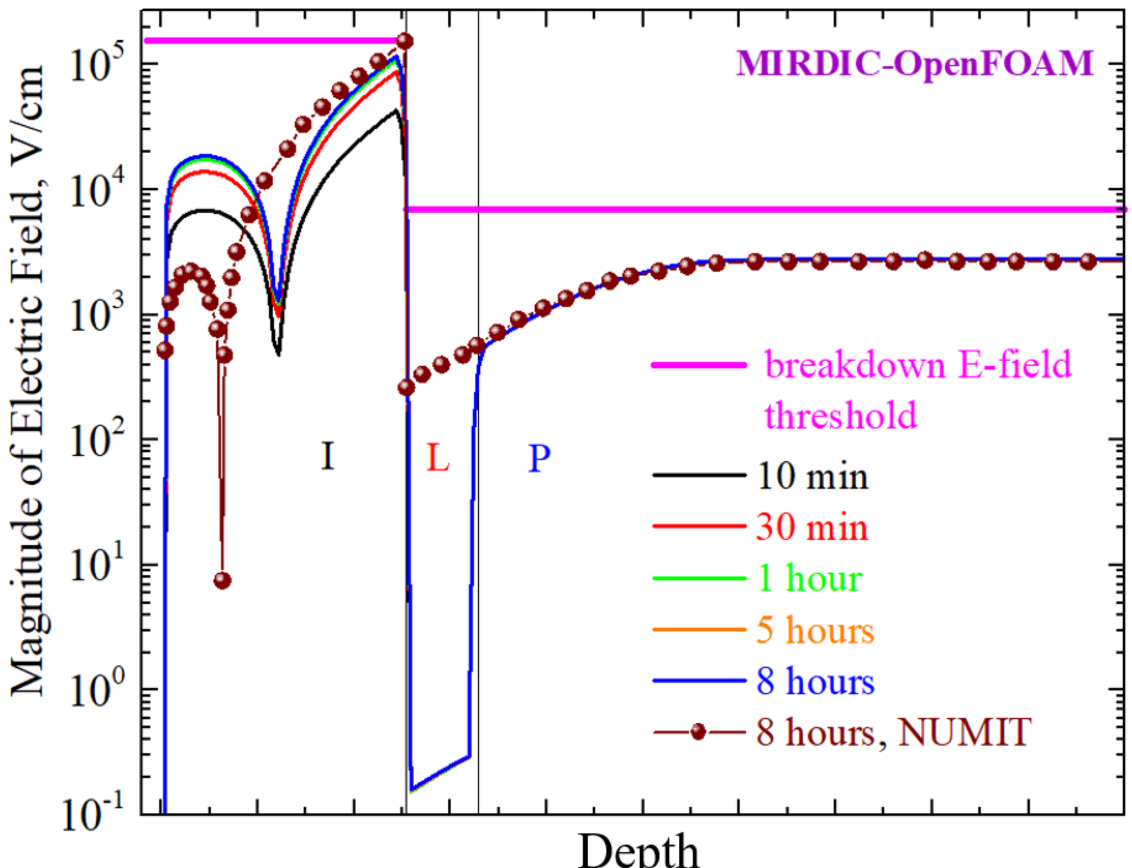
Must Determine:
Does charge exceed breakdown threshold?

Output:



MIRDIC-OpenFOAM Charging

- Collaboration with visiting summer faculty
- Explored coupled charging analysis with Geant4 and OpenFOAM

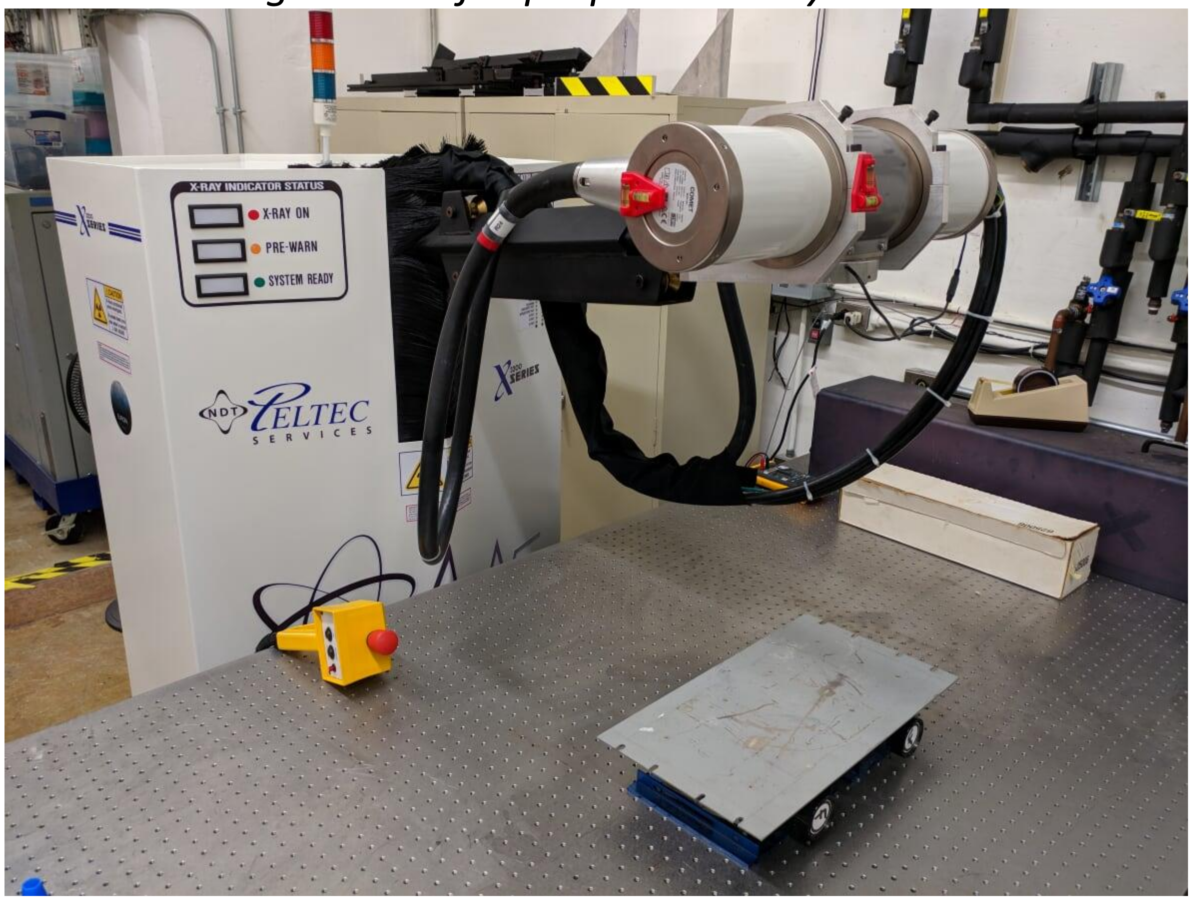


Miloshevsky, G., Caffrey, J., Electron deposition and charging analysis for the Europa Lander Deorbit Stage. NASA Tech Memo in Press. Aug 2018.

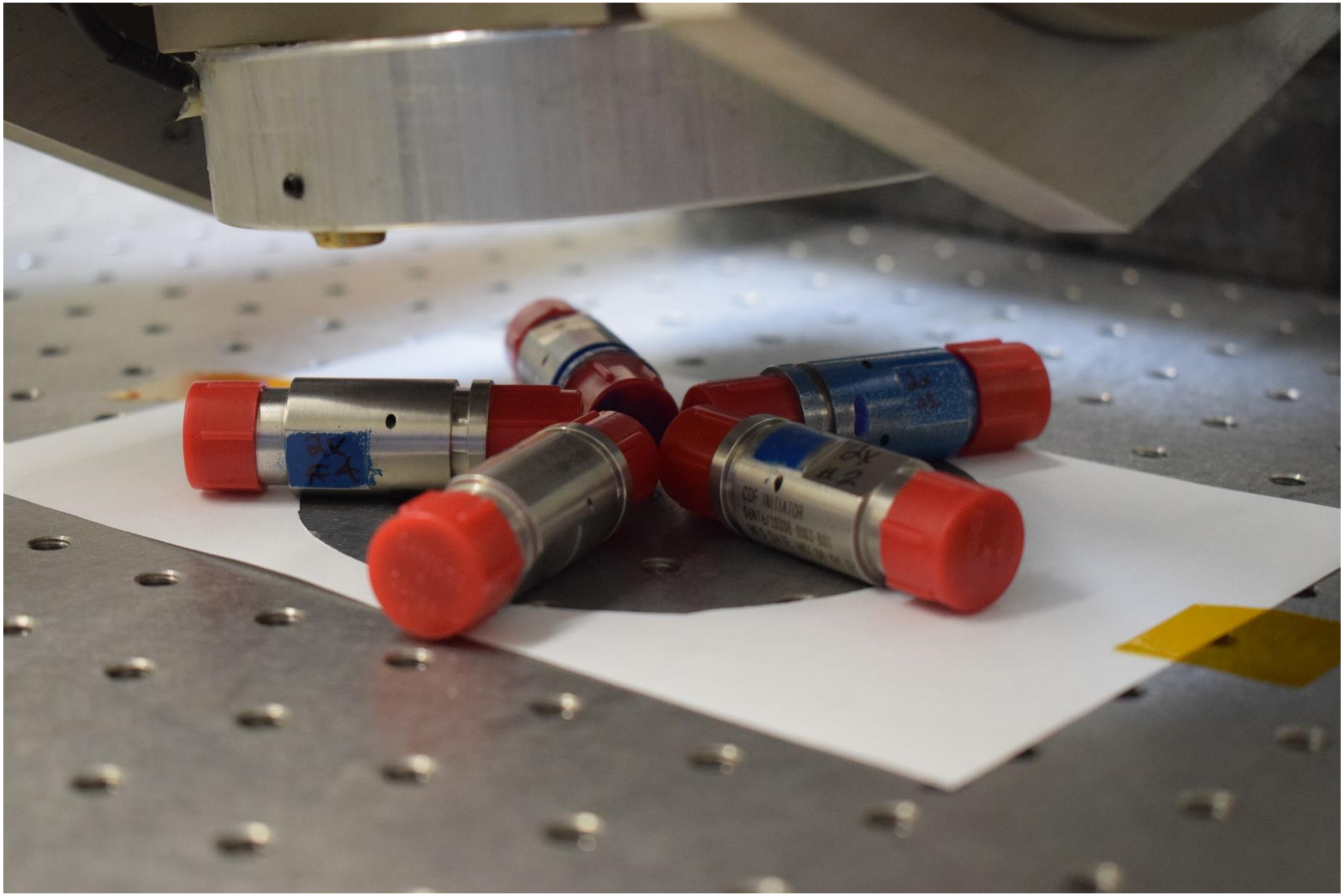
MSFC X-ray Irradiator

Comet MXR-321 Beam Head
4000 Watt Generator
320 kVp Max

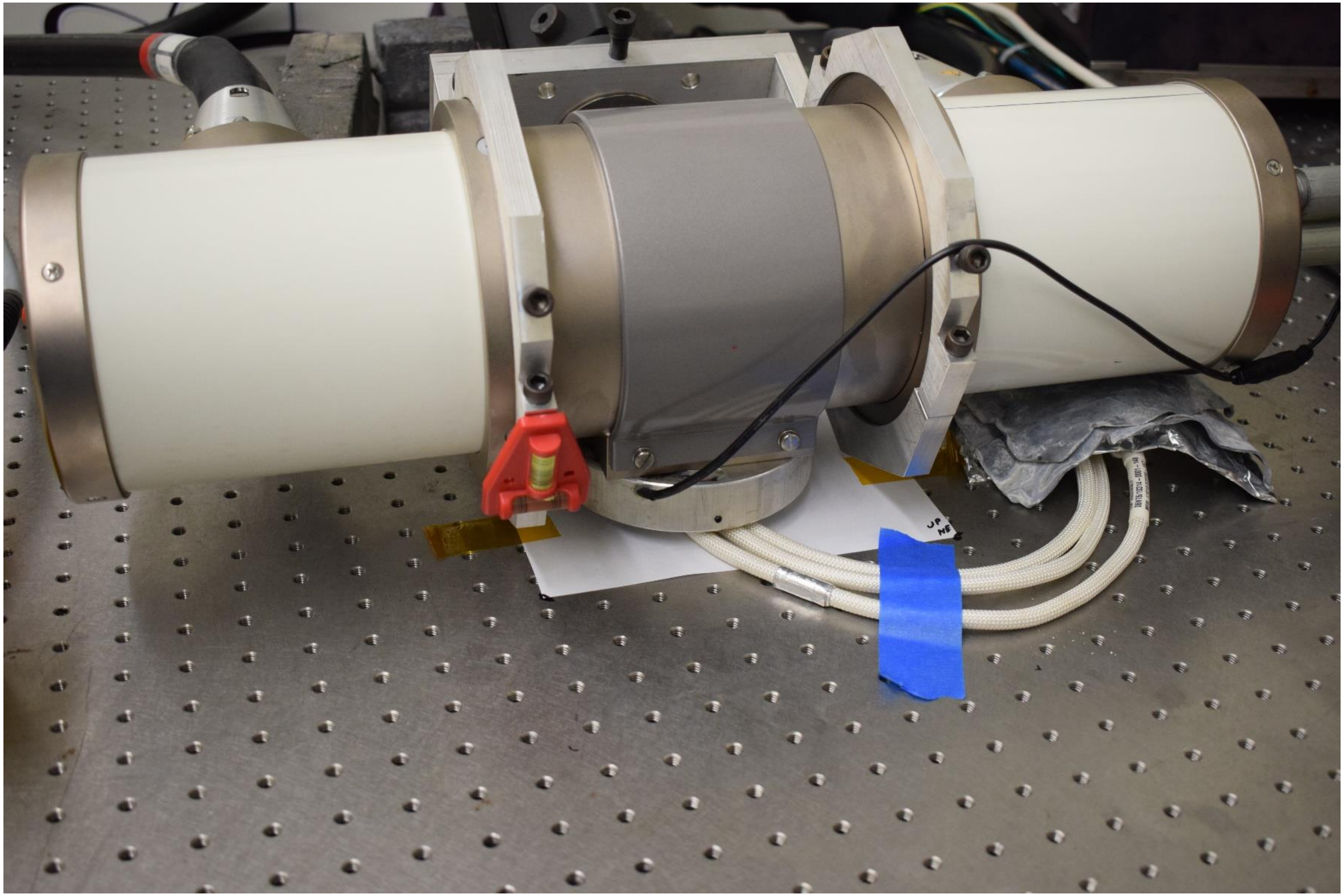
Delivers ~ 1 Mrad/hr to a beam spot of ~10 cm diameter
OR larger areas for proportionately more time



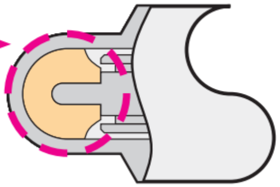
NASA Heritage Confined Detonating Fuse Initiators (CDFI)



NASA Heritage Confined Detonating Fuse Assembly (CDFA)



High-rate Ion Chamber

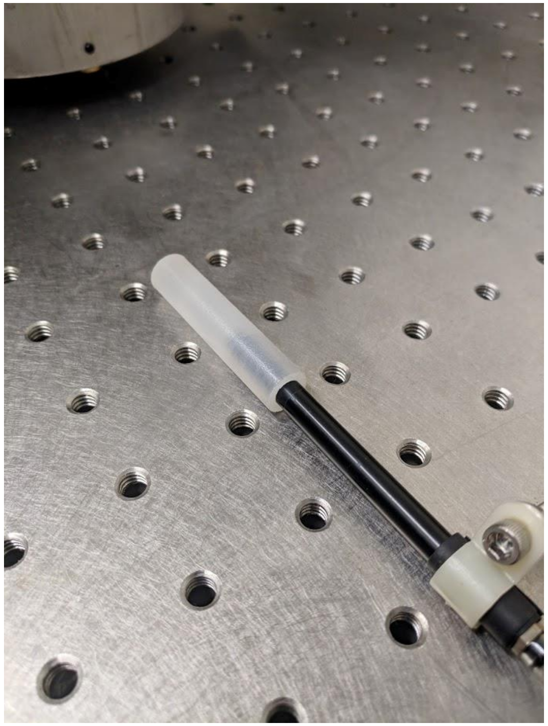


- Exradin A26 microchamber
  - Extremely small dose volume → good spatial resolution
  - Handles extremely high dose-rate fields
  - Fits within 'phantoms' of very small size for shielded dose rate measurement

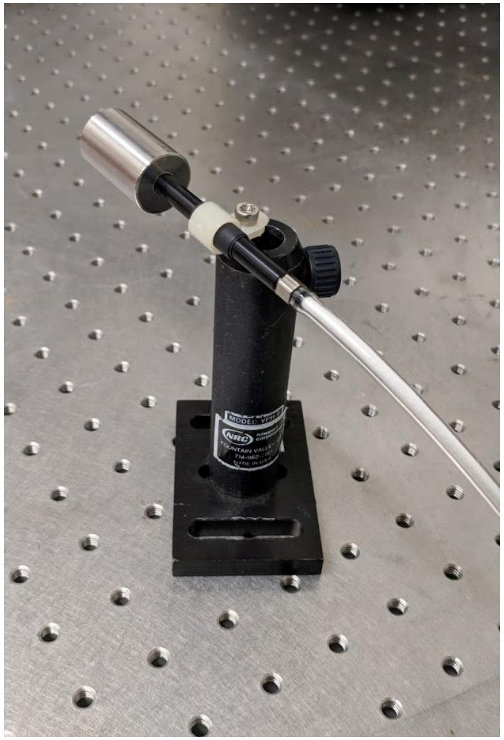
- Max 4000 Plus Electrometer
  - High precision readout device for ion chambers
  - Measures charge collection within microchamber → convert to dose rate

Dose Phantoms for X-ray Calibration

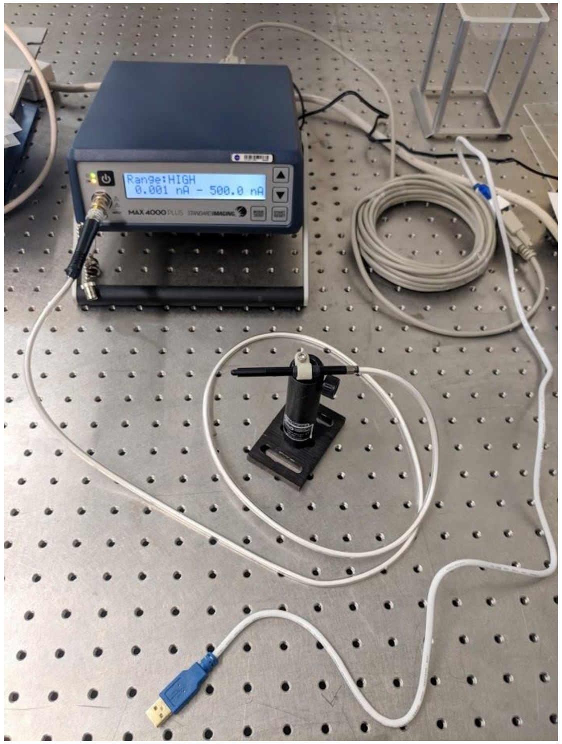
0.08” Polypropylene
(~CDFA)



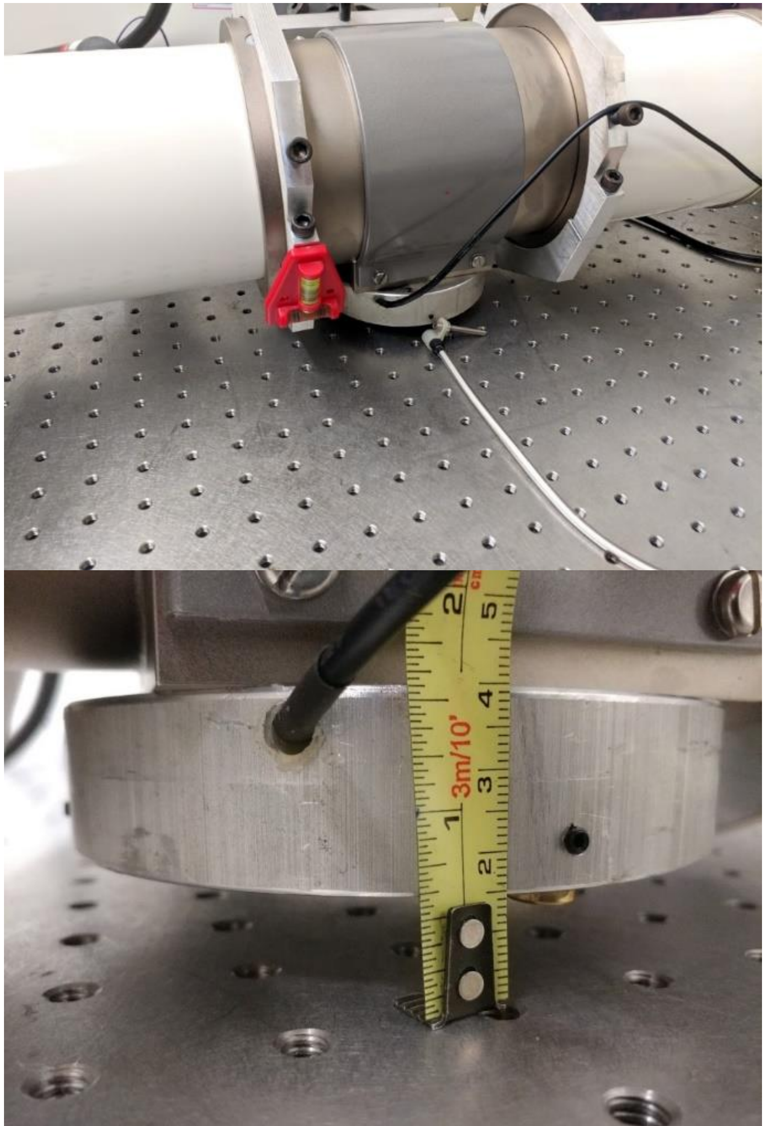
0.25” Stainless Steel
(~CDFI)



Electrometer and Chamber

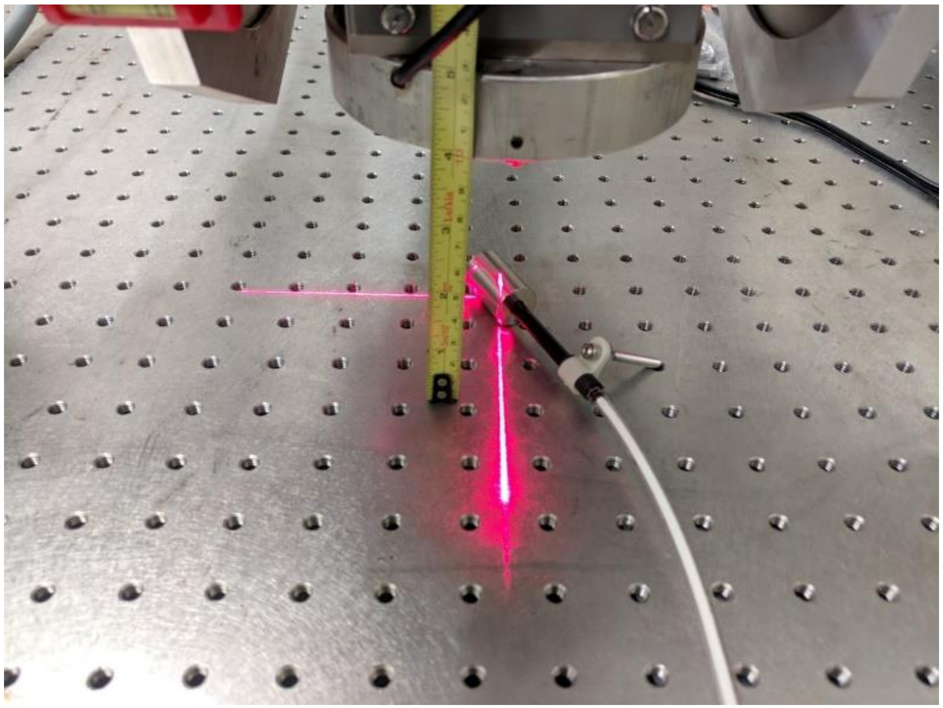


Dose Estimate: CDFA Phantom



Measured rate (11.5 cm)= 510 rad/s		
Rad TID Level	Dose: CDFA	Time (hr)
Level I	None (Control)	0.00
Level II	8 Mrad	4.36
Level III	12 Mrad	6.54
Level IV	16 Mrad	8.71
Level V	32 Mrad	17.43

Dose Estimate: CDFI Phantom



Measured rate (15cm): 19.0 rad/s		
Rad TID Level	Dose: CDFI	Time (hr)
Level I	None (Control)	0.00
Level II	140 krad	2.04
Level III	210 krad	3.07
Level IV	280 krad	4.09
Level V	560 krad	8.18

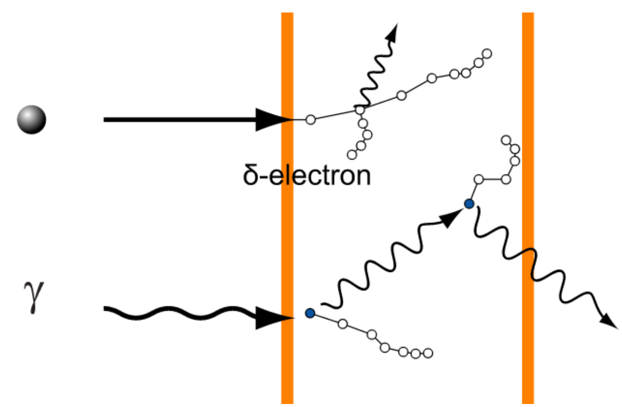
Photons (γ or X-ray) Vs Electron Beam

- More penetrating
- Gammas (γ) are delivered at discrete ‘high’ energies
- X-rays are delivered in spectrum
  - Mostly at lower energy
  - Ramps up to peak energy
- Gammas deliver dose more uniformly
- X-rays can be tailored
- Net neutral charge deposition

At the ‘micro’ level:
TID from electrons = TID from photons
At the ‘macro’ level:
‘Shape’ of dose deposition is different

TID = Total Ionizing Dose

- Readily available facility at MSFC
- Delivers dose very well to thin materials
- Same particle that is directly encountered at Europa BUT
  - TID is the same between photon and electron ionization*



$$\frac{Energy}{Mass} = Dose$$

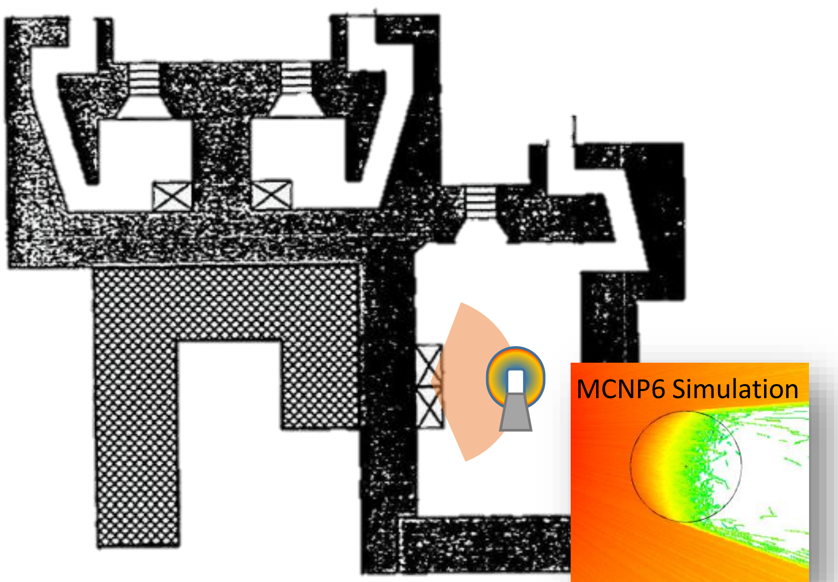
Towards Full Scale Irradiation

- In a perfect world:
  - A world-class facility replicates the exact Europa spectrum
  - They permit a series of loaded SRMs to consume their beamline for months
  - For free
  - Nothing goes wrong

- In our world, select between the following:
  - Large Gamma Irradiator (e.g. GIF at Sandia)
  - X-ray irradiator (MSFC, Vendor, 3rd party)
  - High energy electron beam (Commercial irradiation facility)
  - Abandon full-scale irradiation

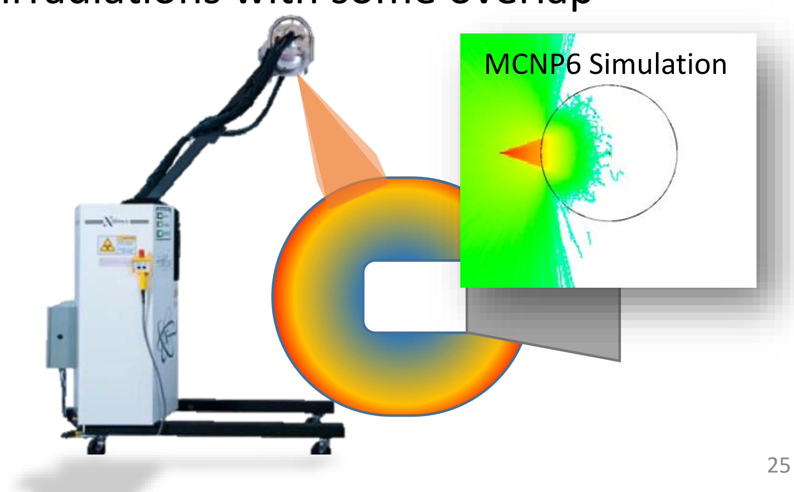
Gamma Irradiator vs X-ray

- Pro
  - Traditional approach
  - Established facility
  - High flux
- Con
  - Uses radioactive sources
  - Regulatory/Safety hurdles
  - Heavily shielded (no blowouts)
  - Gammas are more penetrating, so less representative dose profile

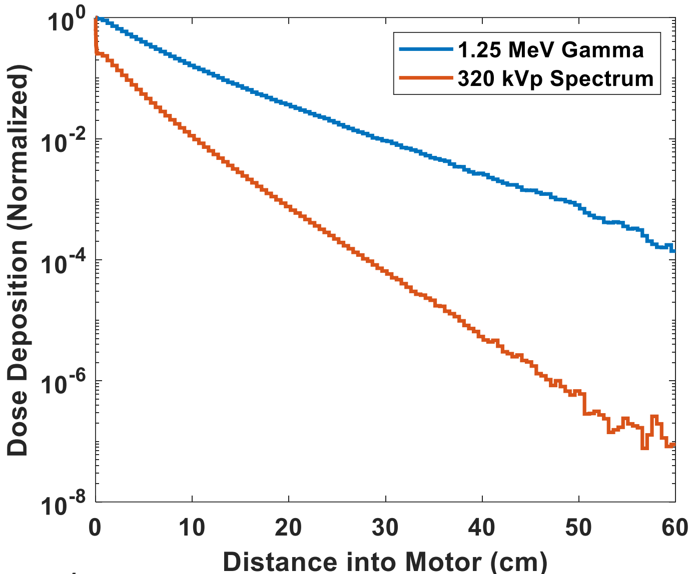


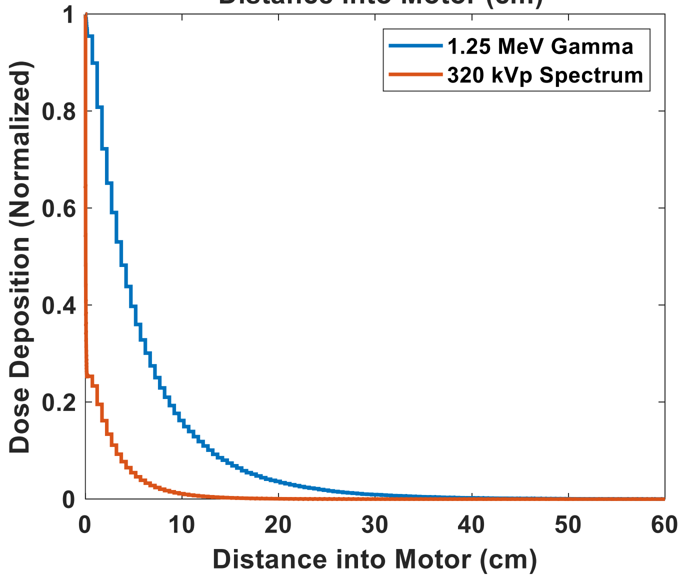
Pro
- No radioactivity
- X-rays are less penetrating
- **Energy can be tailored** to approximate electron dose profile
- May utilize vendor X-ray hardware and processes

- Con
  - Reduced flux
  - Not a traditional approach
  - Small spot size, so multiple irradiations with some overlap



X-ray Irradiation

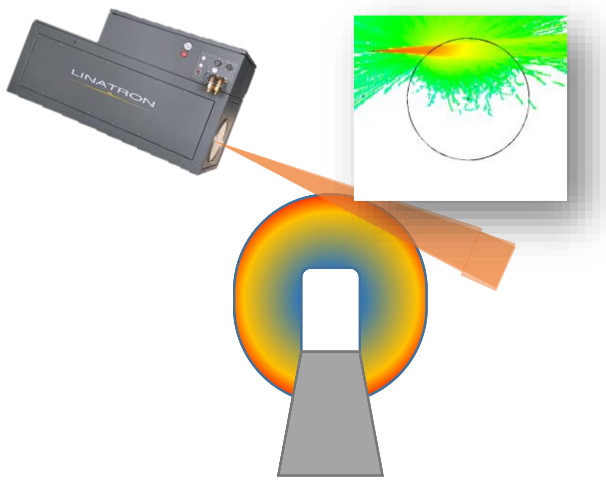




- Steeper attenuation through propellant better matches electron dose profile
- Further 'tuning' with additional lower energy components ***may*** replicate electron dose profile
- X-ray beam heads can be easily moved
- Beam can be focused and directed

<u>NOTIONAL CONCEPTS (TO BE TRADED)</u>

Low/Mid Energy
X-Ray Array



High Energy X-Ray
'Oblique' Shot

Conclusions

- Early risk reduction activities are buying down uncertainty in the Europa Lander project and highlighting focus areas
- Radiation effects at this level are a problem common to many space applications:
  - Europa Clipper
  - Europa Lander
  - Nuclear Propulsion
- MSFC environment effects facilities are a valuable resource for radiation effects testing, even to high doses
- Radiation analysis tools are helping to both plan for the mission environments and to evaluate the experiments themselves
- Significant interaction with customers/stakeholders to evaluate and explain the experiments and dose profiles
- Radiation effects tests are ongoing for both internal and external partners/customers

Questions?